# ROSETTA RADIO SCIENCE INVESTIGATIONS

*Gravity Investigations at Cornet P/Wirtanen*


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Abstract. 'l'he Rosetta Radio Science Investigations (RSI) experiment was selected by the European Space Agency to be included in the International Rosetta Mission to comet P/Wirtanen (launch in 2003, arrival and operational phase at the comet 201 1-2013). The RSI science objectives address fundamental aspects of cometary physics such as the mass and bulk density of the nucleus, the gravity field, non-gravitational forces, the size and shape, the internal structure, the composition and roughness of the nucleus surface, the abundance of large dust grains ant] the plasma content in the coma and the combined dust and gas mass flux on the orbiter. RSI will make use of the radio subsystem of the Rosetta spacecraft.

## 1. Introduction

in February 1996, the Science Program Committee (SPC) of the European Space Agency (ESA) approved the inclusion of the Rosetta Radio Science investigations (RSI) experiment to be carried out during the International Rosetta Mission to comet P/Wirtanen.

In contrast to other *in situ* or remote sensing experiments, a radio science experiment will not install a dedicated onboard instrument. It will make use of the spacecraft radio subsystem which is responsible for the communication between the spacecraft and the ground station on Earth. RSI is interested in the nondispersive (classical Doppler) and dispersive (due to the ionized propagation medium) carrier frequency shifts, the signal power and the polarisation of the radio wave. The analysis of these changes will give information on the motion of the spacecraft, on perturbing forces acting on the spacecraft and on the propagation medium. The carrier frequencies used for the uplink (transmission of telecommands to the spacecraft) are S-band at 2.1 GHz and for the two downlinks (transmission of telemetry data to the ground station) are X-band at 8.4 GHz and S-band at 2.3 GHz. 'l'he measurements will be done at the ground stations. The current mission baseline includes the ESA ground station in Perth, Australia, which will be upgraded to *30-111* over the next few years. The Deep Space Network of NASA with its antenna complexes in California, Spain and Australia is considered as a back-up.

The selected target comet for the Rosetta mission is 46P/Wirtanen, discovered by C.A. Wirtanen (Wirtanen, 1948) in 1948 and recovered for its 1997 apparition by H. Boehnhardt on 26 April 1996 (Boehnhardt et al., 1996a). Wirtanen is a short period comet with a revolution period of 5.5 years and a perihelion distance of 1.08 AU in 1997. The next perihelion passage will be on 14 March 1997 (Marsden, 1996) which means that the comet is now (late 1996) in that segment of its orbit that will be visited by

Rosetta in 2012/2013.

The Rosetta spacecraft will be launched in January 2003 by an Ariane 5. One Mars flyby (August 2005) and two Earth flybys (November 2005 and November 2007) are scheduled in order to gain sufficient $\Delta v$ for intercepting the comet in August 2011 after its aphelion passage at a heliocentric distance of 4.7 AU. The high orbit phase and global mapping will begin in August 2012 at a heliocentric distance of 3.25 AU. The times and heliocentric distances of the close observations and the lander deliveries depend on the actual situation and are still subject to discussion. Rosetta will escort the comet to perihelion from October 2012 to July 2013.

## 2. RSI Primary science objectives

RSI identified primary and secondary science objectives at the comet and during cruise, respectively. The primary science objectives were divided in the categories (a) cometary gravity field investigations, (b) comet nucleus investigations and (c) cometary coma investigations which will be described in the next subsections.

### 2.1. GRAVITY INVESTIGATIONS

The main objectives of the gravity field investigations are the determination of the mass and the bulk density of the nucleus, the harmonic coefficients of the gravity field, the cometary moments of inertia and the non-gravitational forces acting on the nucleus.

#### 2.1.1. *Mass and bulk density; gravity coefficients and moments of inertia*

The determination of the cometary mass and bulk density is a fundamental objective in order to assess the validity and accuracy of various cometary models. Extensive simulation studies, in preparation for the Near-Earth Asteroid Rendezvous (NEAR) mission to asteroid 433 Eros, demonstrate that orbiting a small asteroid will require a gravity field extraction process that is fundamentally different from previous gravity studies of the moons or planets (Scheeres, 1995; Miller et al., 1995). P/Wirtanen is significantly smaller than asteroid 433 Eros and will most likely be active during some portions of the gravity field investigations (Boehnhardt et al., 1996b). Upon arrival at the comet, the a priori knowledge of the nucleus size, shape, mass, activity and spin state will be poorly known. A strategy is needed for an iterative solution of the gravity field.

An initial flyby during the Rosetta approach phase should enable a mass determination to an accuracy of 10% (Yeomans et al., 1981). The current size estimate of the nucleus of 700 m-800 m (Boehnhardt et al., 1996b) suggests a flyby distance within 60 km.

The injection into a bound high orbit allows iterative improvements of the mass determination up to 1 % accuracy. The orbit can then safely be reduced to 20-50 cometary radii (depending on the actual mass of the comet). The second order and degree gravity coefficient ($J_2$ and $C_{22}$) can be estimated using the shape model (from imaging observations) and assuming constant density. The result is a constraint on the true gravity field. In the likely event that the comet is not in perfect principal axis rotation, a knowledge of the body's second order gravity coefficients and a determination of its spin state can be used to determine its moments of inertia; these moments provide constraints upon the internal structure of the nucleus.

The most stable low orbits for the spacecraft would be in equatorial, retrograde orbits about the comet. Beginning with these orbits, the second order gravity field could be solved for in the orbit determination process. Higher order gravity coefficients might be determined from low polar orbits. This attempt also assumes that the cometary outgassing is not introducing significant accelerations upon the spacecraft. First estimates showed that the early activity of comet Wirtanen even beyond 3 AU might generate radial accelerations due to outgassing masking the effects of higher gravity harmonics (Gill et al., 1996). The determination of the higher harmonics would likely be ensured if the gravity mapping campaign takes place at heliocentric distances well beyond 3 AU when the comet is not very active. If the gravity mapping campaign must be undertaken at times when the comet is already active, care must be taken to ensure that the spacecraft does not become adversely perturbed by the outgassing streaming away toward the sunward direction, If the spacecraft orbit could be maintained nearly perpendicular to the Sun-comet line, the outgassing perturbations could be minimized.

From an improved shape model, the volume can be refined and the gravity field can again be approximated using a constant density nucleus. The mass will eventually be known to the 1 % level, volume and density to the 3% level. The shape gravity model (with constant density) and the true gravity model (from spacecraft tracking) are then compared to yield information on the mass heterogeneity of the comet nucleus.

2.1.2. *Non-gravitational* forces

The cometary orbit is also affected by gas and dust emission during the active phase of the nucleus. It is suspected that the effects of the non-gravitational forces of P/Wirtanen may be very different than previously expected to explain the shifted position of its rediscovery in June 1995 from the predicted position (Boehnhardt et al., 1996b). Ground-based astrometry of the comet provides only limited spatial accuracy for orbit determination and suffers furthermore, in particular during the high activity near perihelion, from the offset between the center of light in the coma and the center of gravity of the nucleus (Yeomans, 1986). The position of a spacecraft very close to the comet can be determined very accurately using Doppler and ranging measurements and the positions of the comet with respect to the spacecraft can be determined using on-board imaging observations. These precise observations of the comet's position, along with the comet's existing astrometric data beginning in 1948, will allow a significant refinement to this comet's nongravitational acceleration force model.

### 2.2. NUCLEUS INVESTIGATIONS: SIZE AND SHAPE, INTERNAL STRUCTURE, BISTATIC RADAR EXPERIMENT

Rosetta will be the first spacecraft to use occultation techniques and bistatic radar to explore the cometary interior, the surface and the close vicinity of the nucleus. These techniques are well established and succesfully used for the sounding of planetary rings, atmospheres, ionospheres and surfaces (Marouf et al., 1982; Tyler, 1987; Tyler et al., 1992).

The size, shape and the internal structure of the nucleus will be. investigated by occultation experiments prior, during and after the spacecraft is occulted by the nucleus as seen from the Earth. Accurate measurements of the ingress and egress occultation times determine the length of the occultation chore] for a known spacecraft trajectory, hence constrain the size of the nucleus. Repeated measurements for different occultation track geometries constrain the nucleus shape. Occultation observations are most useful when imaging observations arc not possible, e.g. for observations of the night-side or when the limb of the nucleus is obscured by dust.

Because the nucleus is a small body, the interior or the upper layer of the nucleus may be penetrable by microwaves. The refractive properties of the nucleus will modify the propagation of the radio signal so that it might be possible to constrain the bulk refractive index of the nucleus.

A bistatic-radar experiment was proposed to measure the scattering properties of the nucleus, hence determine the physical nature of the surface and its material properties. Rosetta's orbit around the nucleus allows measurements of the strength and state of polarisation of the X-band radio signal transmitted by Rosetta and scattered by the nucleus over a broad range of Spacecraft-Con)et-Earth angles. The shape and strength of the co- and cross- polarised components of the echo spectra can be used to differentiate between asteroid-like diffractive surface scattering (Harmon et al., 1989) and icy-bodies-like volume scattering. Furthermore, for the circularly polarised incident wave, observation of the bistatic scattering angle determines the Brewster angle $\gamma_B$ of the surface material, hence its dielectric constant $\epsilon$. Thus, independent differentiation between an icy conglomerate ($\gamma_B \sim 50°$, $\epsilon \sim 1.4$) and very dusty ($\gamma_B \sim$ GO", $\epsilon \sim 3$) surfaces can be achieved, in principle. Similar bistatic radar observations were used to determine $\epsilon$ of the lunar crust (Tyler and Howard, 1973) and the Martian surface (Simpson and Tyler, 1981).

### 2.3. COMA INVESTIGATIONS

The abundance of mm-dm size dust particles very close to the nucleus, the plasma content of the very inner coma inaccessible to orbiter *in situ* measurements and combined dust and gas mass flux perturbing the Rosetta orbit are the objectives of the cometary coma investigations.

Radar observations of comets Iras-Aracki-Alcock (Harmon et al., 1989) and Halley (Campbell et al., 1989) revealed a dust grain size population between a few mm and probably as large as 10 cm distributed about the nucleus out to 1000 km. The wavelengths of the Rosetta radio subsystem are in the same bands used in the radar studies mentioned above. One observable of the cometary grain sounding experiment will be the signal attenuation along the ray path from the spacecraft to the Earth, expressed as the differential optical depth $\tau(3.6\ \mathrm{cm}) - \tau(13\ \mathrm{cm})$. These measurements provide constraints upon grains in the mm - dm size range (Marouf et al., 1982). The second observable is the power incoherently scattered in the near-forward direction. Because of the motion of the grains relative to Rosetta and the Earth, the scattered signal is Doppler shifted, spread over a finite bandwidth centered on the frequency of the direct ray.

The first radio sounding observations of a cometary ionosphere were performed with the VEGA spacecraft at comet P/Halley (Andreev and Gavrik, 1990; Pätzold et al., 1996). Observations at two coherently related frequencies are required to separate the dispersive contribution due to the propagation of the radio wave from the classical Doppler shift. First estimates showed that a phase shift at both frequencies is detectable for gas production rates between $10^{27}...10^{28}$ molecules sec$^{-1}$.

The motion of the Rosetta spacecraft about the nucleus will be perturbed by radial accelerations due to gas and dust impinging on its surface. It is therefore possible to determine the combined gas and dust mass flux and its variation with distance from the nucleus, the variation with heliocentric distance and the variation of coma and jet activity with illumination. In contrast to the Giotto flybys (Pätzold et al., 1991), the main perturbations are expected to be due to gas jet interactions than to dust grain impacts. Together with the gravity field modelling, RSI will be able to constrain the maximum liftable mass and will also be able to provide an estimate of the overall gas and dust production rate.

### 2.4. ASTEROID FLYBYS

Rosetta will perform two flybys at asteroids Mimistrobell and Rodari (the current second target asteroid) in September 2006 and August 2008, respectively. The determination of the mass and bulk density of these objects depends crucially on the flyby distances. Currently, the planned flyby distances are too large to allow meaningful mass estimates for these two asteroids.

## 3. RSI secondary science objectives

The Rosetta spacecraft will pass through five superior solar conjunctions and three solar oppositions and additionally two conjunctions and one opposition during cruise and the prime mission, respectively, providing the opportunity for radio sounding of the inner solar corona and the search for gravitational waves.

## 4. Measurement technique

It is required to modify some components of the spacecraft radio subsystem in order to improve the sensitivity and accuracy of the measurements. These components are the on board oscillator and the capability to transpond or transmit simultaneously two phase coherent downlinks at S-band (2.3 GHz) and X-band (8.4 GHz) with the constant coherency ratio of 11/3 which makes it feasible to separate the dispersive Doppler effects from the nondispersive Doppler effects.

The measurements at the ground station can be done simultaneously with the transmission and reception of telecommands and telemetry, respectively. Two radio link modes will be used. The routine operational radio link mode is the two-way link with a S-band uplink and a coherent and simultaneous dual-frequency downlink (S- band and X-band) via the High Gain Antenna (HGA) of the spacecraft. This takes advantage of the superior stability of the ground station frequency reference source generated by the hydrogen masers. The one-way link mode (simultaneous coherent dual-frequency downlink) is used only during an occultation of the spacecraft by the nucleus as seen from the Earth. These occultation experiments require an Ultra Stable Oscillator (USO) on the spacecraft. The prime purpose of the USO is to serve as a phase coherent frequency source for the simultaneous downlink transmissions. The required stability (Allan variance) of the USO is about $\Delta f/f \sim 10^{-13}$ at 10 - 1000 seconds integration time. Space qualified oscillators of this stability have been provided to many interplanetary space missions for radio science purposes.

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## References

Andrew, V.I. and and Gavrik, A.L.: 1990, "Distribution of electron density at comet P/Halley from radio science data", *Kosmicheskie Issledovaniya* 28, 293-303.

Boehnhardt, H., Rauer, H., Motolla, S. and Nathues, A.: 1996a, *IAU Circular No. 6392.*

Boehnhardt, H., Babion, J. and West, R.M.: 1996b, "An optimized detection technique for faint moving objects on a star-rich background", *Astron. Astrophys.*, in press.

Campbell, D.B., Harmon, J.K. and Shapiro, 1.1.: 1989, "Radar observations of comet Halley", *Astrophys. J. 338, 1094-1105.*

Gill, E., Montenbruck, O. and Pätzold, M.: 1996, "Perturbation forces acting on the Rosetta spacecraft in a close orbit around comet P/Wirtanen", *AAS paper 96-150,* Houston.

Harmon, J. K., Campbell, D.B., Hine, A. A., Shapiro, 1.1. and Marsden, B.G.: 1989, "Radar observations of comet Iras-Aracki-Alcock (1983d)", *Astrophys. J.* 338, 1071–1093.

Marsden, B.G.: 1996, *Minor Planet Circular No. 27081.*

Marouf, E. A., Tyler, G. L. and Eshleman, V. R.: 1982, "Theory of radio occultation by Saturn's rings", *Icarus* 49, 161193.

Miller, J. K., Williams, B.G., Bellman, W.E., Davis, H.P., Helfrich, C.E., Scheeres, D.J., Synnott, S.P., Wang, T.C. and Yeomans, D.K.: 1995, "Navigation analysis for Eros rendezvous and orbital phases", *Journ. Astronautical Sci.* 43.453-476.

Pätzold, M., Bird, M.K., Volland, H., Edenhofer, P. and Buschert H.: 1991, "Dynamics of the Giotto spacecraft in the inner dust coma of comet P/Halley; Part I: Observations", *Z. Flugwiss. Weltraumforsch.* 15, 89-96.

Pätzold, M., Neubauer, F.M., Andreev, V.E. and Gavrik, A.L.: 1996, "Detection of the inner plasma pile-up region at comet Halley during the VEGA-1 flyby by the radio sounding experiment", *J. Geophys. Res.*, in press..

Scheeres, D. J.: 1995, "Analysis of orbital motion around 433 Eros", *Journ. Astronautical* Sri. 43, 427-452.

Simpson, R.A. and Tyler, G. L.: 1981, "Viking bistatic radar experiment: summary of first-order results emphasizing north polar data", *Icarus 4G. 361-389.*

Tyler, G. L.: 1987, "Radio propagation experiments in the outer solar system with Voyager", *Proceedings of the IEEE* 75, 1404-1431.

Tyler, G.L. and Howard, 11.1.:1973, "Dual-frequency bistatic-radar investigations of the Moon with Apollos 14 and 15", *J. Geophys. Res.* 78, 485? ---1874.

Tyler, G.L., Simpson, R.A., Maurer, M.J. and Holmann, E.: 1992. "Scattering properties of the Venusian surface: Preliminary results from Magellan", *J. Geophys. Res.* 97, 13115-13140.

Wirtanen, C. A.: 1948, "Comet 1948b", *IAUC 881.*

Yeomans, D.K.: 1986, "Physical interpretations from the motions of Comet Halley and Giacabini-Zinner", ESA *SP-250 II,* 419-425.

Yeomans, D.K., Ananda, M., Sjogren, W.L. and Wood, L. J.: 1981, "Cometary mass determination", *Journ. Astronautical Sci.* 29, 19-33.